A COMPARISON OF ADHESIVE BONDING PROCESSES AND TRAINING STANDARDS IN DEFENCE AND CIVIL AVIATION INDUSTRY[1]

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ABSTRACT:

This paper identifies the basic requirements for durable adhesive bonded repairs, and identifies deficient procedures that are in common use. In particular, based on interviews with technicians who have been assessed as competent IAW the NACS, the standards of training in adhesive bonded repair processes in the Australian Defence Forces are compared to those delivered within the civil National Aerospace Competency Standards (NACS). This paper finds that the NACS competencies do not meet the required standard for composite and adhesive bonded repair technology, and recommends that the ADF continues to require that personnel working on State aircraft must meet the specific Defence Enterprise Competencies. The deficiencies in civil standards derive from the failure to differentiate between the two distinct and separate technologies of "composite materials" and "adhesive bonding". It is also recommended that an Advisory Circular be developed to provide guidance on the verification of procedures for design, certification and application of adhesive bonded joints and repairs.

Introduction

Adhesive bonding technology has been in use for repair of aircraft structure for many years. Adhesive bonded sandwich structure has always been repaired using adhesive bonded doublers applied over repaired honeycomb core. In 1975, the Defence Science and Technology Organisation [1] developed adhesive bonded repair technology for non-sandwich structure applications such as repair or reinforcement of fatigue and stress corrosion cracks and corrosion damage in aircraft skins and sub-structure. While the crack repair technology has had extensive use in Defence applications, there is still reluctance for more widespread use of this technology within Defence. The use of adhesive bonded repairs for civil aircraft applications is almost non-existent, despite the well established history of long term performance on Defence aircraft worldwide. Hence, many aircraft operators are failing to avail themselves of the significant advantages offered by adhesive bonded repairs.

Part of the reason for the low usage rate of adhesive bonded repairs is the poor experience operators have had with adhesive bonded repairs over the history of service of sandwich structure. The authors assert that the poor performance of bonded repairs is a result of deficiencies that have been allowed to establish themselves throughout the entire technology, and which continue to be perpetuated by inadequacies in design, certification, validation and implementation of adhesive

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bonding technology from original manufacture through to repair implementation. Deficiencies are further propagated by inadequate training standards for technicians and engineers.

The authors contend that these deficiencies are largely due to the confusion and blurring between two distinct and separate technologies, composite materials and adhesive bonding. There is a common confusion between composite materials (high strength fibres embedded in a resin matrix) and composite construction methods such as adhesive bonded sandwich structure. It is a fundamental error to believe that because a technician has competency in fabrication of fibre-glass or carbon composites that the technician also has competency in preparation of a metallic surface for adhesive bonding of that patch. Hence the National Aerospace Competency Standards (NACS), its underpinning curriculum and the CASA requirements for LAME training all assume that competency in composite materials also conveys competency in adhesive bonding. This is simply not the case.

To assess the level of skill provided under the NACS, interviews have been conducted by the authors over the last five years with civil and service personnel prior to and during training on the ADF adhesive bonding course conducted at RAAF Base Amberley. These people had undertaken the underpinning training for NACS MEA405A (Repair Aircraft Composite Material Components) as part of their initial trade training. The training is delivered by a number of recognised training providers. These interviews reveal that the level of training provided by many Registered Training Organisations (RTOs) falls far below the level of training necessary to achieve acceptable levels of competency in adhesive bonded repair technology. These findings are of importance in considerations relating to the use of contractors to perform maintenance on ADF assets.

This paper will outline the fundamental requirements for adhesive bonding and provide examples of where these requirements are not being met by current airworthiness regulations, some Original Equipment Manufactures, and a significant number of approved Structural Repair Manuals, and some RTOs. The deficiencies identified in current wide-spread accepted practice were sufficient to prompt RAAF to develop their own standards and handbooks for adhesive bonded repair technology.

The authors warn that continuing progression along current processes for certification, validation and training may eventually result in catastrophic failure of flight-critical structure, with consequent risks to passengers and potential exposure to litigation that will be difficult to defend.

ADF Adhesive Bonded Repairs

Based on many years of successful experience with adhesive bonded repair technology developed by the Defence Science and Technology Organisation, The Australian Defence Forces recognised that for effective adhesive bonded repairs to be used as a maintenance tool for Defence aircraft, the sound scientific basis for the technology must be codified and incorporated into a structured framework that would enable reliable implementation of adhesive bonded repairs. This has resulted in the development of an engineering standard DEF (AUST) 9005 (formerly RAAF STD ENG C5033). That standard is supported by two enabling documents:

- AAP 7021.016-1 *Composite and Adhesive Bonded Repairs: Engineering and Design Procedures,* and

- AAP 7021.016-2 *Composite and Adhesive Bonded Repairs: Repair Fabrication and Application Procedures.*

These publications form the basis for three training packages:

- ADHESBONDTECH, which provides the underpinning skills for technicians,
- ADHESBONDMAN, which provides the underpinning skills for supervisors and managers of adhesive bonded repairs , and
- ADVCOMMATADBONRD, which provides the skills for bonded repair design engineers.

Each of these courses provides the underpinning training for specific ADF Enterprise Competency Standards respectively:

- DDDRAC201B *Perform Adhesively Bonded Repairs to Aircraft Structures and Components*
- DDDRAC502A *Manage the Adhesive Bonding Function*
- DDDREN511A *Design Adhesively Bonded Repairs* (awaiting approval).

The working maintenance system is supported by a Quality Management system, based on establishing standards in storage and handling of materials (DEF (AUST) 9014), annual requalification of repair technicians and supervisors and regular audits of facilities and maintenance management systems.

As a consequence of the manner in which adhesive bonded repairs are managed, the repeat repair rate at Amberley has been reduced from 43% in 1992 to almost zero [2]. Unfortunately, the same can not be said for other bases where a moderately small number of bonded repair failures have been reported. These failures have been investigated and usually the causes are the use of OEM specified surface preparation processes that are known to be inadequate, or the inappropriate use of hot-bonding equipment used for repair application. Where failures have occurred, the procedures used were NOT those specified within the RAAF system, or the approved procedure was not correctly followed.

Adhesive Bonding Fundamentals: Design

The non-uniform nature of shear stresses in adhesive bonded joints has been well known for many years [3, 4]. Adhesive shear stresses peak at the ends of a joint and decay to zero if sufficient overlap length is provided. Once the overlap length is sufficient to enable the shear stresses to decay to zero, the addition of further overlap length does not change the shear stresses in the joint because the additional overlap adds to the zero shear stress trough in the centre of the joint.

Valid design data can be derived from the Thick Adherend Test ASTM D3983-93, and the design data must be generated over the entire temperature range expected in the service envelope for the joint. That data is used to calculate the adhesive load capacity of the joint at the temperature extremes, based on the work of Hart-Smith [4]. The joint load capacity is compared against the maximum design load case for the minimum and maximum temperatures to determine if the joint is strong enough to carry the required load, with an appropriate margin of safety. The author has detailed this approach in a number of previous papers to which the reader is referred [5, 6].

Using this approach, it is actually possible to design bonded joints such that there is a very high level of confidence that the adhesive bond will *never* fail (provided the processing issues discussed in this paper are also addressed).

Observed Deficiencies in Bonded Joint Designs

Adhesive bonded joints have been traditionally designed on the basis of comparison of the average shear stress in the bond against a “design allowable” average shear stress derived from an extensive test program, usually based on lap-shear tests such as ASTM D1002. By necessity, that approach requires large safety factors to be applied to reduce the allowable stress to a level where failure is unlikely. Typically, [7] a design allowable stress of 500 psi may be applied to a design where the actual adhesive shear strength as measured by a lap-shear test would approach 5000 psi. Clearly, such designs can result in very inefficient bonded structures.

Of more concern, in cases where thick, stiff adherends are being joined, the design may be unconservative, even after applying such significant safety factors. Hence, if a designer using an average shear stress method was to increase the overlap length on the mistaken belief that the shear stresses will be reduced, it is possible that the actual strength of the joint could be exceeded. There is also a risk that the high degree of damage tolerance that can be derived from bonded joints can be significantly compromised. In reality, the lap-shear test does *not* provide data that can be used for design of a bonded joint. The only valid application of the lap-shear test is as a quality control measure.

Adhesive Bonding Fundamentals: Surface Preparation Processes

To correctly implement adhesive bonding processes, it is essential to understand the mechanisms behind the formation of an adhesive bond. For an adhesive bond to be effective and durable there must be chemical reactions that form strong chemical bonds at the interface between the adhesive and substrate [8]. It is these chemical bonds that establish the strength of the adhesive bond, and it is the degradation of those chemical bonds that leads to most cases of adhesive bond failure.

Once the chemical nature of the process is understood, then the processes necessary to achieve those chemical bonds can be deduced by simple logic. To achieve bond strength, there are three fundamental requirements:

- The surface must be clean and free of contaminants that would inhibit the chemical reactions between the adhesive and substrate,
- The surface must be chemically active to enable the chemical reactions to occur, and
- The adhesive must be provided with the conditions (usually the cure temperature) that initiate the chemical reactions and permit them to continue until the reaction is complete.

If the surface preparation processes meet these requirements, then a strong adhesive bond can be readily obtained. The surface must be prepared by at least solvent degreasing and either abrasion or etching processes to expose a chemically active surface.

However, even if a strong bond is achieved, there is no guarantee that this bond will sustain that strength throughout its service life. The most common cause of adhesive bond failures is degradation of the chemical bonds at the interface between the adhesive and substrate, and the most common cause of degradation is hydration of the surfaces as moisture is absorbed by the adhesive or substrate. For example, the surface of aluminium adherends will oxidise rapidly to form Al_2O_3. The adhesive reacts with that oxide layer to form the chemical bonds necessary for adhesion. In service however, aluminium oxide has a high affinity for the formation of the hydrated oxide $Al_2O_3.2H_2O$. To form the hydrated oxide, the chemical bonds between the adhesive and the substrate dissociate, leading to interfacial disbonding (adhesion failure).

Hence, if adhesion failure is to be prevented, there must be some process undertaken *at the time of surface preparation,* to prevent hydration of the chemical bonds between the adhesive and the substrate. This usually requires some form of chemical treatment after the chemically active surface is exposed. The only exception to this requirement is where there is a strong acid-base reaction between the adhesive and the substrate.

Observed Deficiencies in Surface Preparation Processes

A common misconception with adhesive bonding is that scuff-sanding followed by solvent cleaning will provide strong adhesive bonds. This is only true if the bond strength is measured shortly after manufacture, because that process does not contain steps that would provide resistance to hydration of the bond.

Not all chemical treatments in common use actually provide durable adhesive bonds. Experimental evidence [9] and anecdotal evidence from F-111 experience has shown that chromic acid etching does not provide bond durability, despite the fact that this process has been widely used for many years. Similarly, the use of Alodine treatment prior to bonding can never produce bond durability because the Alodine process is a corrosion *passivation* process, and the surface produced is not conducive to the production of effective chemical bonds.

Observed Deficiencies in Surface Preparation Training

A significant number of tradespersons who had completed training in composite repair have been interviewed in relation to the surface preparation processes for metal bonding in which they were instructed and assessed as competent. Earlier interviews revealed that the process used was the Boeing "Clean and Finish Repair Parts with HF/Alodine [10]. However, instruction in that process actually omitted the use of the corrosion inhibiting primer specified in the reference. Later tradesmen indicated that they had observed the phosphoric acid non-tank anodising process (PANTA). However, while PANTA is extremely effective as a surface preparation process, it is extremely messy, has a high risk of causing corrosion in adjacent areas and is difficult to perform on sandwich structure or on vertical surfaces.

More recent interviews of tradesmen who had been trained in another organisation indicated that some had exposure to a hand abrade and silane process that was withdrawn by RAAF in 2003. Later training had used the HF/Alodine process. It was indicated that the only experience gained in metal bond preparation was to manufacture a 25 mm square area on a lap-shear specimen.

Given the fundamental importance of surface preparation to adhesive bond strength and durability, the authors contend that this level of training is grossly inadequate. It certainly fails to meet ADF standards as detailed in DEF (AUST) 9005 and would appear to be inadequate for repair performance on civil aircraft.

Adhesive Bonding Fundamentals: Adhesive Cure Processes

To cure an adhesive bond requires control of three variables:

- Temperature, to enable the chemical reactions to occur,
- Time, to enable the chemical reactions to proceed to completion, and
- Pressure, to control the void content in the bond and to hold the components in place while the adhesive cures.

The control of temperature is fundamental to ensuring that the bond is fully effective. A low temperature will result in under-curing of the adhesive, while excessive temperature may result in over-heat damage to the structure. In production environments, heating may be performed using autoclaves and ovens, but for on-aircraft repair heat is usually supplied by heater blankets or heat lamps.

To achieve full cure, the repair area must achieve the required cure temperature throughout the adhesive layer. For even moderately complex structure, the presence of heat sinks and materials with differing thermal properties can have a very significant influence on temperature distribution, and hence the degree of cure and/or the risk of overheating the structure. To achieve a reasonable temperature distribution requires a visual assessment of the distribution of thermal masses in the heated zone, and the allocation of a *separate* heat source for each zone. Thus, even for moderately complex structure, multiple heat sources will be required.

The control of the heating process requires the use of thermocouples to measure the temperatures. Thermocouples perform two primary functions:

- To control the heating process to prevent overheating of the structure, and
- To provide assurance that the adhesive has achieved the required cure temperature.

For control of the heating process, thermocouples must be located at the location under *each* heat source at sufficient locations such that there is certainty that the *hottest* temperature in that zone will be identified. That sensor must be used for control of the power to the heat source. For assurance of adhesive cure, thermocouples must be located around the repair such that there is certainty that the *coldest* temperature in the bondline is measured. That sensor must be used as a measure of acceptance of the repair heating process.

The rate of temperature increase also has a significant effect on the adhesive bond. Excessive heat-up rates result in the volatiles released during the heating process being trapped because the adhesive gels rapidly before the volatiles have a chance to escape. If a slow heat-up rate is used, then the polymers in the adhesive layer cross-link within the adhesive layer before the adhesive has had a chance to flow and wet the surface. This results in very few chemical bonds between the adhesive and the substrate, with consequent poor bond strength. The failure surface appears to be interfacial and often these failures are incorrectly attributed to poor surface preparation.

Observed Deficiencies in Adhesive Cure Processes

Unfortunately, many aircraft repair manuals fail to recognise the significant effect on temperature distributions caused by even moderate sub-structure, and these manual typically specify the use of a single heater blanket for all repairs. Similarly, these manuals typically specify the use of a standard configuration for thermocouple numbers and placement, such as four thermocouples located 90º apart around the repair. The deficient outcome of these processes is often masked by the fact that the results will depend strongly on where the first thermocouple is placed. Obviously, the locations shown in case "A" in Figure 1 will give a different outcome from the locations chosen in "B" in that Figure. If the technician uses the configuration "A" the result will appear to be successful with a relatively uniform temperature distribution reported by the hot-bonder. In reality without the information about the temperature over the sub-structure, the information provided will provide a false sense of the performance of the system and a deficient repair.

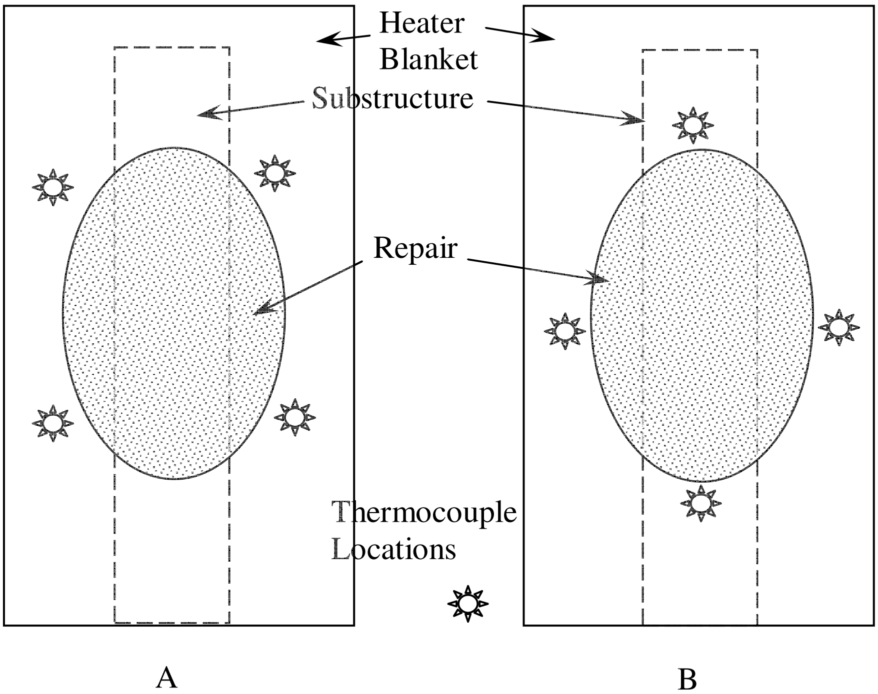

Figure 1. A schematic representation of the influence of alternative thermocouple placements on repair outcomes.

Another common error in adhesive curing processes is to locate thermocouples on a copper sheet which is positioned over the repair. This approach will successfully report only the temperature of the copper sheet, not the structure. To demonstrate the deficiency in this approach, simply place the entire heating system on a bench away from the repair zone, and operate the system. It will report a successful achievement of the cure temperature, despite the fact that it is nowhere near the repair site.

The manner in which the hot-bonding equipment is used also influences the outcome of the repair. A number of repair manuals specify the use of the lowest temperature to control the heating process. The objective is to ensure that the entire heated zone achieves the cure temperature. However, there is an increased risk of overheat damage to the structure within the heated zone.

Observed Deficiencies in Adhesive Cure Training

Interviews with technicians who had undertaken training and were assessed as competent IAW NACS MEA405A indicated that the underpinning skills to achieve this competency were apparently never delivered by any of the training providers. In all cases, the performance of hot-bonded repairs was undertaken by placing specimens prepared by the students into a recirculating air oven to cure the adhesive and/or patch resin system. Not one student reported having observed the use of a hot-bonding system to cure adhesives.

Given the strong influence of temperature measurement and control on repair integrity, the authors contend that the failure to adequately address this competency presents an unacceptable risk to the airworthiness of composite and adhesive bonded repairs.

Adhesive Bonding Fundamentals: Certification of Bonded Structures and Repairs

Current certification bases such as DEF STAN 00 970, FARs, JARs or MIL HDBK 1530 all require demonstration of static strength, fatigue resistance and to a varying extent damage tolerance. The problem with this approach for adhesive bonded structures is that it is actually possible to generate sufficient short-term strength in adhesive bonds by the use of processes that do not provide long term bond durability. This is particularly true of processes that do not provide resistance to hydration for the interface. Hence, it may be possible to verify static strength, fatigue resistance and damage tolerance for a structure and have it fully certified, only to find that in service the adhesive bonds fail.

The traditional approach to certification of adhesive bonded structures broadly follows the "building block" approach advocated in Advisory Circular 20-170-A for composite structures, see Figure 2. This approach is aimed at building confidence in the structure by a gradual approach to a certifiable design.

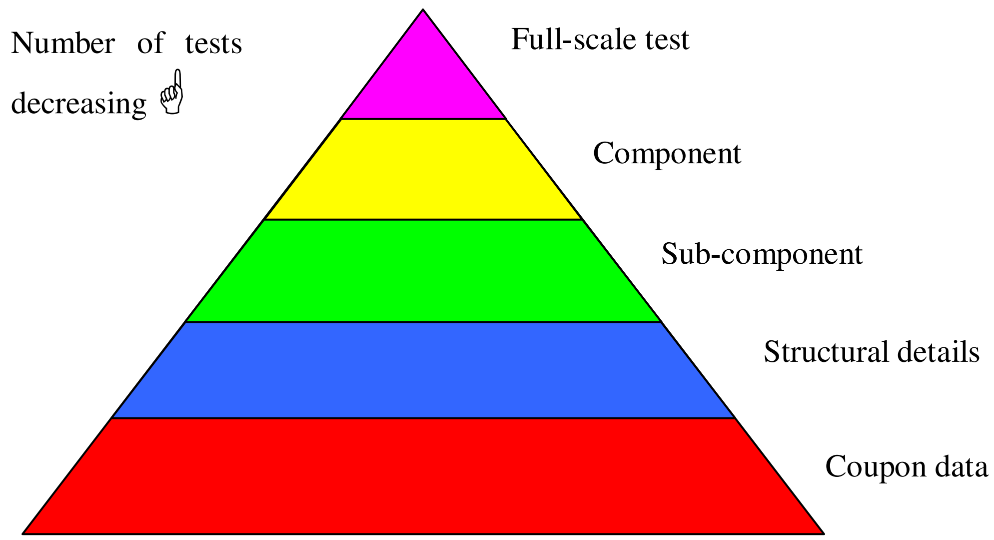

Figure 2. A schematic representation of the building block approach to certification of adhesive bonded structures.

Structures certified by this approach are usually expensive due to the large number of tests required. Many coupon specimens are required to develop the "design allowable" stress with a sufficient margin of safety to assure that bond failure is improbable, and then a significant number of tests follow to demonstrate that the various configurations of materials being joined, the different material thicknesses involved, the service temperatures and environmental conditions and the applicable overlap lengths still provide adequate joint strength. These tests are followed by a moderate number of sub-component tests on those critical structural features where failure of the bond may be critical to safety. Further tests are then conducted on a number of entire components to verify structural strength. The final tests are conducted on the entire structure to verify static strength, fatigue resistance and damage tolerance.

In contrast, consider the outcome of designing a bonded joint on the basis that the adhesive load capacity will *always* exceed the design loads for the given temperature case, with an appropriate margin of safety. In such designs, the risk of joint failure is dramatically reduced because the adhesive bond should *always* be stronger that the surrounding structure. *Hence the bond is removed from the design consideration as a failure mode*. The adjacent structure will always be critical, not the adhesive bond.

With such a high level of confidence in the integrity of the bond, the cost of certification testing may be dramatically reduced, with no cost to flight safety. For a start, the number of tests for generation of design data (please, not design "allowables") is substantially lower because *actual* design properties are measured and these are NOT modified to provide the margins of safety which are derived by the design methodology, not fudged into the design data. Next, the multiple tests to demonstrate that structural features and sub-components have appropriate strength may be eliminated or at least reduced to a very small number of tests, because all tests should fail *outside the joint*. What is the sense in undertaking hundreds of tests where the failure always occurs outside the joint and the adhesive never fails?

In effect, the certification program may be reduced to a smaller number of tests to generate *actual* design data, a few tests to demonstrate that failure always occurs outside the joint and the usual component and full scale tests, see Figure 3. The savings in certification costs would be substantial, as would the increased level of confidence in adhesive bonded structures, *provided that the processing issues are dealt with before the structure is fabricated and tested.*

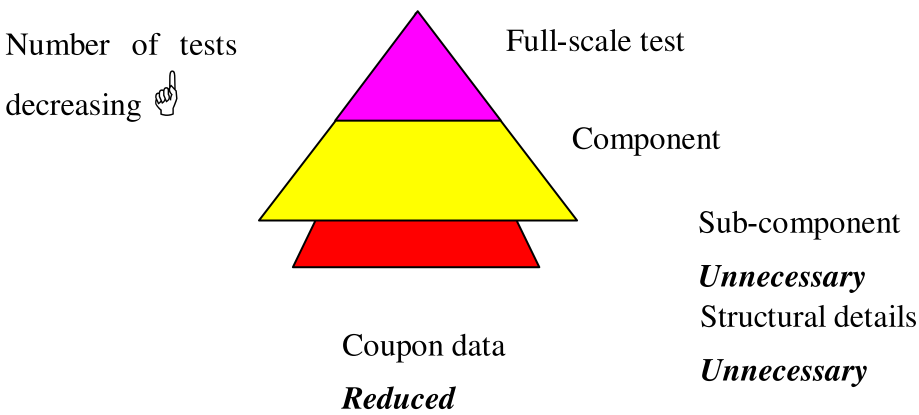

Figure 3. A reduced certification test program where the adhesive bond load capacity is designed to always exceed the structural loads.

Certification of Adhesive Bonding Processes

Clearly, if an appropriate certification basis for a bonded structure is dependent on valid processing to produce durable adhesive bonds, then there is a requirement to adequately demonstrate the long-term durability of adhesive bonds produced by the proposed production methods. Because certification is usually based on static strength, the common practice is to use lap-shear tests to demonstrate that processes produce acceptable adhesive bonds.

In fact the FARs stipulate that the processes must “produce a consistently sound structure” (see FAR 25.605 for example). The problem is that there is no definition on what constitutes a “sound” structure. If static strength and fatigue testing are recognised as demonstrating structural soundness, then the issue of gradual time-based deterioration of bond strength is ignored. Further, FAR 23.573 for example requires that *Repeatable and reliable non destructive inspection techniques must be established that ensure the strength of each joint.* It must be clearly understood that currently there is no Non Destructive Inspection(NDI) procedure that can determine if an adhesive bond has the potential for degradation in service. NDI can only identify air gaps in an adhesive bond after the bond has failed, it can not provide assurance that the bond will maintain integrity in future service.

What is required is that in addition to demonstration of strength and fatigue resistance, it is essential to demonstrate that production and repair *processes* consistently produce bonds with long-term bond durability, i.e. resistance to hydration. It has been concluded by an international collaborative effort [11] between Defence organisations from USA, UK, Canada, New Zealand and Australia (The Technical Co-Operation Program, TTCP Action Group 13) that the most effective accelerated test to demonstrate long-term bond durability is the wedge test ASTM D3762, where 1 inch wide and 6 inch long specimens were wedged apart by a standard wedge whilst exposed to a hostile environment, typically 50ºC and 95% RH. The crack growth rate in the specimens is monitored and used as a measure of the reliability of the process.

However, the criteria stated in ASTM D3762 (an average of 0.5 inches and a maximum of 0.75 inches in one hour out of five specimens) were considered by TTCP-AG13 to be substantially deficient. The TTCP recommendation is that for a process to be considered valid for adhesive bonding, there must be no more growth than 0.25 inches in 48 hours environmental exposure, and that there must be no more than 5% adhesion failure (interfacial failure) in the test zone.

Hence, the TTCP-AG13 advocate that the surface preparation processes must be validated to the above requirements *before* the structure or repair is subjected to the usual certification procedures. The authors strongly support this position, and advocate that there is a requirement for an advisory circular for adhesive bonding technologies, similar and distinct from AC-20-170A for composite structures.

The processes that are known to produce durable bonds include the Australian Grit Blast and Silane process [12], Boeing’s Sol-Gel process when combined with grit blasting [13], Boeing’s Sol-Gel process when combined with hand-abrasion using a specific abrasive pad [14] , and Phosphoric Acid Anodising (PANTA or PACS) provided that the surface temperature is less than 29ºC [15].

Management of adhesive bonded repairs in general

Reliable adhesive bonded repairs require careful, considered application of validated processes to produce long-life durable repairs. In practice pressures to make an aircraft serviceable to meet mission deadlines are often used as an excuse for the implementation of bad practices. The assertion that improper practices are justified in order to meet maintenance schedules must be challenged for both Defence and civil operations, firstly from an airworthiness perspective and secondly on a cost of ownership basis.

It must be clearly understood that for a flight-critical structure there is absolutely no justification whatsoever for placing the safety of an aircraft, the passengers and crew at risk by the use of ineffective bonding practices. For non-critical structure ineffective methods may be appropriate for *temporary* repairs only, to permit short term operations until the next scheduled major servicing. The problem at present, in particular for civil aviation, is that there is no clear delineation between a temporary repair procedure and those more suited to a life-of-type repair. As a consequence the same ineffective repair procedures are implemented for flight-line repairs and also for deeper maintenance repairs. One author has observed a bonded repair to a composite trailing edge flap that has been repeated several times as a matter of routine *every* time a particular civil 737 aircraft undergoes C checks. *If effective bonded repair processes are correctly implemented, repeated application of the same repair should not be necessary at all.*

The basic requirement should be that where less effective processes are used, then that repair must be clearly documented as a temporary repair and it must be replaced at the next available opportunity using processes that have been correctly validated to produce strong, durable adhesive bonds. Unless there is irrefutable evidence that a process can produce long-term bond durability, then the repair must be seen only as a temporary measure. Continued use of ineffective processes that result in repeated performance of the same repairs using the same procedures that resulted in bond failure not only exposes the operator and/or repair station to legal action in the event of structural failure, but also adds significantly to maintenance costs associated with repeated repair applications.

Conclusions

Based on the ADF experience with a very low repeat repair rate, there are significant outcomes provided by the development of the ADF composite and adhesive bonded repair system of a standard, handbooks, quality management system, ADF Enterprise competency standards and underpinning training. The ADF training system has identified and addressed critical aspects of adhesive bonding technology that have not been adequately managed by the NACS. Interviews with technicians who have been assessed as competent to MEA405A clearly demonstrate that the level of training is significantly inferior to that provided in-house by the ADF.

Recommendations

The following recommendations are made:

- That the ADF must not accept a decline in standards in composite and adhesive bonded repairs, and must require contractors to achieve the competencies developed by the ADF.

- That the standard of delivery of training by civil organisation must be audited by persons who are subject matter experts in composite and adhesive bonded repairs.
- That the NACS be expanded to correctly address the significant differences between "composite technology" and "adhesive bonding technology".
- That an Advisory Circular (AC) be developed to address the design and certification of adhesive bonded structures and repairs. That AC must address the requirement for and manner of certification of bonding processes.

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